GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 8, PAGES 1183-1186, APRIL 15, 2000

Projected impact of climate change on the freshwater and salt budgets of the Arctic Ocean by a global climate model

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Abstract. The annual flux of freshwater into the Arctic Ocean by the atmosphere and rivers is balanced by the export of sea ice and oceanic freshwater. Two 150-year simulations of a global climate model are used to examine how this balance might change if atmospheric greenhouse gases (GHGs) increase. Relative to the control, the last 50-year period of the GHG experiment indicates that the total inflow of water from the atmosphere and rivers increases by 10% primarily due to an increase in river discharge, the annual sea-ice export decreases by about half, the oceanic liquid water export increases, salinity decreases, sea-ice cover decreases, and the total mass and sea-surface height of the Arctic Ocean increase. The closed, compact, and multi-phased nature of the hydrologic cycle in the Arctic Ocean makes it an ideal test of water budgets that could be included in model intercomparisons.

1. Introduction

The long-term freshwater balance of the Arctic Ocean is maintained by inflow from the atmosphere and rivers and outflow through the ocean. The freshwater outflow consists of sea-ice export and an oceanic component that results from the transports of water masses of different salinities across the southern boundary of the Arctic Ocean. There are still uncertainties in the magnitudes and variability of all of the terms in this freshwater balance of the Arctic. Superimposed on these uncertainties is the possibility that the balance is changing in time either at shorter time scales associated with the North Atlantic and Arctic Oscillations or at longer time scales associated with climate change.

The Arctic region is one of the key areas to understand in trying to assess how climate might change in the future because it is where the powerful ice-albedo feedback mechanism operates. This feedback leads most global climate models to find enhanced warming in the northern hemisphere polar regions in transient studies with increasing atmospheric greenhouse gases [*Houghton et al.*, 1996]. Potential changes in sea-ice cover will be occurring simultaneously with changes in precipitation, evaporation, and river flow. The combined effects of all these changes will alter the ocean circulation and the freshwater and salt budgets of the Arctic Ocean.

Paper number 1999GL007001.
0094-8276/00/1999GL007001$05.00

Although there are some observational records to identify trends in the Arctic Ocean, satellite data sets are only two decades old, and there is generally not enough long-term information to determine whether the trends are part of natural decadal variability or are the manifestation of climate change. Global climate models have the potential to address this question to some extent because they can simulate longer term trends.

The purpose of this paper is to use two 150-year simulations from a global climate model to examine how the Arctic freshwater balance might change in the future in response to increases of atmospheric greenhouse gases. The first simulation is a control with constant 1950 atmospheric composition, and the second is a GHG experiment with observed greenhouse gas concentrations from 1950 to 1990 and with compounded 0.5% annual increases in CO_2 after 1990.

2. The Global Climate Model

The global synchronously coupled atmosphere-ocean model used in this study was developed by *Russell et al.* [1995] for climate studies at decade to century time scales. There are nine vertical layers in the atmosphere and 13 in the ocean. The horizontal resolution for both the atmosphere and ocean is 4° in latitude by 5° in longitude. The resolution for heat, water vapor, and salt is finer than the grid resolution because those quantities have both grid-box means and directional gradients which are used in the advection by the linear upstream scheme. Atmospheric condensation and ocean vertical mixing are performed on $2^{\circ} \times 2.5^{\circ}$ horizontal resolution. The model has several new features including a new ground hydrology scheme, four thermodynamic layers for glacial ice and sea ice, advection of sea ice, glacial ice calving off Antarctica but not in the Northern Hemisphere, and the k-profile parameterization (KPP) ocean vertical mixing scheme of *Large et al.* [1994]. The model does not use flux adjustments.

Unlike rigid-lid ocean models, the present ocean model conserves mass and not volume, has a free surface, and does not use the Boussinesq approximation. The model conserves mass of salt globally at all times and uses natural boundary conditions for precipitation, evaporation, and river flow. The model transports mass, salt and heat through 12 sub-resolution straits including the Nares Strait on the west side of Greenland. Continental runoff and glacial ice melting eventually find their way back to the oceans via a river network. In spite of glacial ice melting and Antarctic calving, precipitation accumulates on the ice sheets, on a few cold grid boxes, and on grid boxes with no river outlet. This causes the

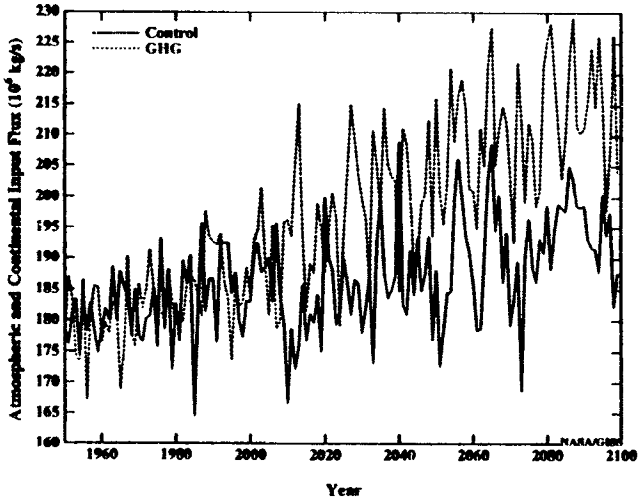

Figure 1. Annual net freshwater inflow to the Arctic Ocean due to river flow and atmospheric input (precipitation minus evaporation) for control and GHG simulations.

Table 1. Mass Budget of Arctic Ocean

	Control	GHG Experiment minus Control		
	1950-2099	1950-99	2000-49	2050-99
Precipitation	90.15	2.84	5.23	14.01
Evaporation	39.91	1.62	2.25	10.65
Precip-Evap	50.24	1.22	2.99	3.36
Rivers				
Mackenzie	19.17	- 0.48	1.43	0.72
Sver.Dvina	3.96	0.05	- 0.25	0.16
Ob	25.24	- 0.07	1.15	1.03
Yenesei	15.68	- 0.41	1.52	0.96
Lena	19.50	- 0.65	0.99	1.88
Kolyma	10.46	0.04	0.21	1.30
N.American	32.31	- 0.23	2.97	7.57
Eurasion	103.90	- 0.26	5.78	8.88
Total River	136.21	- 0.49	8.75	16.45
Total Inflow	186.44	0.73	11.74	19.81
Outflow				
Fram St. Ice	36.55	- 0.51	- 1.12	- 15.85
Total Sea Ice	48.19	- 0.65	- 1.89	- 21.45
Liquid Fresh	138.14	0.40	12.17	37.00
Total Outflow	186.33	- 0.25	10.28	15.55
Net Fresh Inflow	0.11	0.98	1.45	4.26
Net Salt Inflow	- 1.48	- 0.39	- 1.22	- 2.10
Net Mass Inflow	- 1.37	0.58	0.23	2.16

Units in 10^6 kg s^{-1}. River flow includes glacial ice meltwater.

ocean's mass to decrease slowly and salinity to increase over time. For this study the area of the Arctic Ocean is 107 km^2 and does not include the Greenland-Iceland-Norwegian Sea nor Baffin Bay which were included in the previous study of *Miller and Russell* [1995].

3. Changes in Arctic Ocean Freshwater Budget

The components of the freshwater budget for the Arctic Ocean consist of inflow from the atmosphere and rivers and outflow of sea ice and oceanic liquid freshwater. Figures 1 to 4 show how these inflows and outflows vary during the 150-year control and GHG simulations, and Table 1 provides a further breakdown of the individual components. Figure 1 shows the model's total freshwater inflow (river flow plus precipitation minus evaporation). For the control, the inflow increases from 182M (M = million kg s^{-1}) for the first 50 years to 192M during the last 50 years of the simulation, with a mean of 186.44M. For the first half of the simulations, the control and GHG inflows are about the same. During the last 50 years of the GHG experiment, the inflow has increased by 19.81M which is about 10% higher than the control.

Based on Table 1 the control simulation's annual precipitation onto the Arctic Ocean is 0.764 mm day^{-1} which is somewhat higher than observed values of 0.523 mm day^{-1} and 0.695 mm day^{-1} given by *Shea* [1986] and *Legates and Willmott* [1990]. The control's total atmospheric inflow (P - E) to the Arctic Ocean is 0.426 mm day^{-1} which is about the same as the observed value of 0.474 mm day^{-1} of *Walsh et al.* [1994] but significantly higher than *Aagaard and Carmack's* [1989] 0.25 mm day^{-1}. For both the control run and GHG experiment, there is a gradual increase in P - E. For the control run, this is primarily due to a downward drift in evaporation, and in the GHG case it is due to an increase in precipitation. Relative to the control there is a small increase (0.029 mm day^{-1}) in P - E for the last 50 years of the GHG experiment. This increase accounts for about 17% of the increase in freshwater inflow to the Arctic in the GHG experiment.

Most of the increase in freshwater inflow to the Arctic Ocean in the GHG experiment is from river discharge as shown in Fig. 2 and Table 1. For the control, the mean annual river inflow of 136.21M is 13% higher than the observed inflow of *Gordeev et al.* [1996] and about 30% higher than that of *Aagaard and Carmack* [1989] and *Walsh et al.* [1994]. Table 1 shows that river flow has increased by 16.45M during the last 50 years of the GHG experiment, which is a 12% increase relative to the control.

The changes in the model's freshwater outflow due to sea ice and oceanic liquid freshwater transport are shown in Figs. 3 and 4. For the entire basin, the sea-ice export in the control is 48.19M. In the GHG experiment it decreases by 44% for the last 50 years. The model's export through the Fram Strait is about half of the observed transport of 80.5M obtained by *Aagaard and Carmack* [1989], although a more recent study

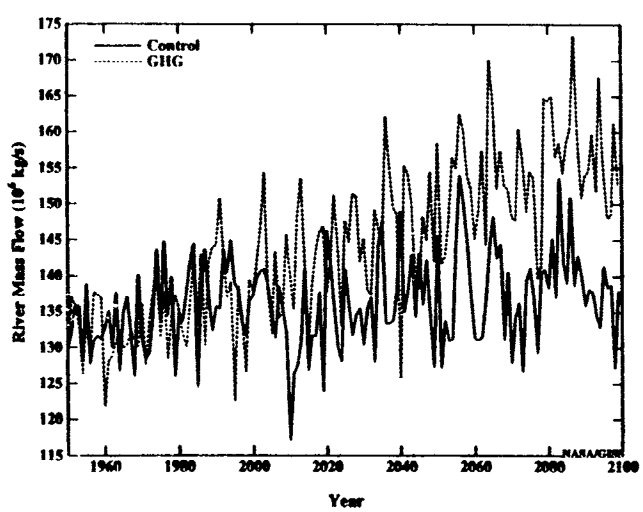

Figure 2. Annual river discharge into the Arctic Ocean for control and GHG simulations.

Table 2. Arctic and Global Sea Level Changes (mm)

	GHG Experiment minus Control		
	1950-99	2000-49	2050-99
Arctic Steric Expansion	20.18	110.64	312.24
Global Steric Expansion	13.27	84.36	209.70
Arctic Water Mass Change	10.91	90.45	222.35
Global Water Mass Change	8.63	34.70	120.99
Arctic Sea Level Change	31.08	201.09	534.60
Global Sea Level Change	21.90	119.05	330.69

by *Steele et al.* [1996] found that the annual observed transport through Fram Strait was 55M for the period from 1978 to 1990. Because the model's Arctic sea ice is too thin, the model's sea-ice mass export is too small even though the model's horizontal area of sea-ice export through the Fram Strait is close to observed values.

If the freshwater inflow increases and the sea-ice export decreases, then either the Arctic salinity will decrease or the liquid ocean freshwater export will increase. All of these occur in the GHG experiment. Figure 4 and Table 1 show that the liquid freshwater export increases by 37M or 27% for the last 50-year period. The model's total freshwater outflow (oceanic liquid freshwater plus sea-ice advection) increases by 15.55M.

As Table 1 shows, the freshwater budget for the control simulation is nearly in balance (a net 0.11M import of freshwater). When this is combined with a net salt export of 1.48M, there is a net Arctic mass outflow in the control of 1.37M or 4.24 mm $year^{-1}$. This can be compared with the global loss of 4.58 mm $year^{-1}$ to snow that accumulates on the ice sheets and to continental runoff that drains into grid boxes without a river outlet.

The mean salinity of the Arctic Ocean can decrease in response to changes in freshwater influx or salt export. Both of these factors cause the Arctic salinity to decrease in the control simulation and to decrease more rapidly in the GHG experiment. Table 1 shows that the combination of increased river discharge and decreased sea-ice export drives more salt out of the Arctic, which causes the water in the Arctic to be less saline in the GHG experiment than in the control.

Table 2 shows that the 535mm increase in the sea-surface height of the Arctic Ocean for the last half of the 21st century is due to both the increasing net mass inflow and to the loss of salt which increases the specific volume. The table shows the relative importance of the two processes and shows that the increase in sea level height in the Arctic Ocean is 62% greater than the global increase.

Table 3 shows how sea ice changes in the GHG experiment. Both sea-ice cover and sea-ice mass decrease. The larger percentage decrease in sea-ice mass indicates that the sea ice is also thinner in the GHG than in the control.

Table 3. Arctic temperatures (C) and sea-ice parameters

	Control	GHG minus Control		
	1950-2099	1950-99	2000-49	2050-99
Ocean Surface Temp.	- 1.32	0.06	0.13	0.38
Ice Surface Temp.	-14.62	0.46	1.15	2.82
Composite Temps.				
Ocean & Ice Surface	-12.83	0.61	1.49	3.69
Surface Air Temp.	-13.08	0.58	1.42	3.41
Ocean Ice Cover (%)	86.54	- 1.65	- 3.91	10.81
Ice Thickness (m)	2.33	- 0.05	- 0.14	- 0.27
Frozen Mass (10^{12} kg)	18693	- 744	-1885	-4305

Composite temperatures are area weighted from separate ice and open ocean fractions. Ice thickness (m) is the ratio of ice and snow mass (kg m^{-2}) divided by the model's constant ice density of 910 kg m^{-3}.

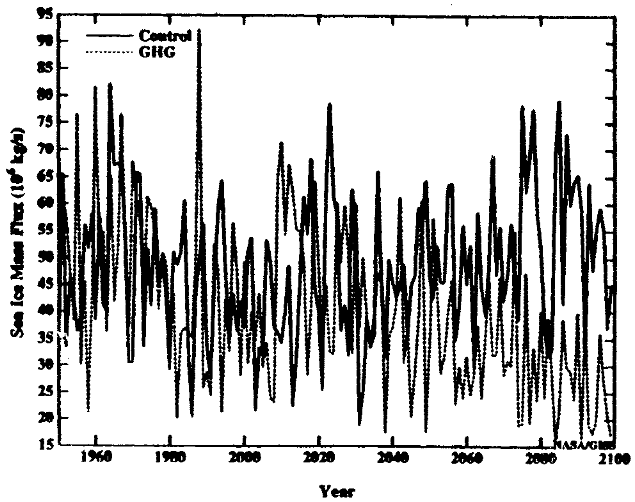

Figure 3. Annual net sea-ice transport out of Arctic Ocean for control and GHG simulations.

4. Discussion and Conclusions

The purpose of this paper is to examine the water budget of the Arctic Ocean and how it might change in response to increases of atmospheric greenhouse gases. The results show that for the GHG experiment the inflow (P - E + R) increases by 10% primarily due to increased river discharge, the sea-ice export decreases by 44%, and the oceanic liquid freshwater outflow increases by 20%. The combined effects lead to increases in Arctic mass and sea level and a decrease in salinity.

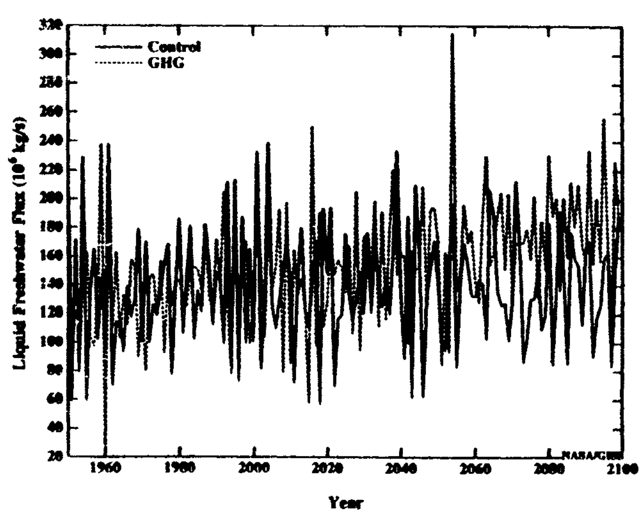

Figure 4. Annual net oceanic liquid export of freshwater from the Arctic Ocean for control and GHG simulations.

To put this work into its proper context, it is important to note some of its shortcomings. The coupled model uses a resolution that is coarse for this region. There is some drift in the model's 150-year control run, particularly in the evaporation. The model's river flow into the Arctic is too high by 10-15%. The export of sea ice from the Arctic Ocean through Fram Strait is too low by about half or 30% depending on the choice of observed sea-ice export. Another problem is that the model's transport through the Canadian Archipelago is too high, primarily because the passages are too wide in the model. *Rudels* [1986] indicates that estimates of mass export through the Archipelago range from 1000M to 3000M compared to the model's export of 5700M.

In spite of the above shortcomings, we believe that the model does have some significant strengths for this type of study and does address some interesting questions. The model's atmospheric flux into the Arctic Ocean agrees with the observations of *Walsh et al.* [1994]. The model is internally consistent and does allow water to be added directly to ocean grid boxes because it has a free surface ocean. The model attempts to conserve water globally and move it among its various reservoirs. The model's global water cycle is not completely closed: some continental runoff drains into grid boxes without a river outlet, and excess snow accumulates on the ice sheets and at some cold grid boxes with insufficient melting, evaporation, or calving.

The results here differ from a recent modeling study by *Zhang et al.* [1998] who used an ocean model driven by observed atmospheric forcing for the period from 1979 to 1996. They found an increase in incoming warm salty Atlantic water since 1989 which leads to a significant warming and salinification in the Arctic Ocean in agreement with recent observations. Our results our consistent with the increased temperature but not with the increased salinity. The forcing used to drive their model was quite different, particularly because their river flow is constant and not increasing with time as it is in the GHG experiment here.

The global hydrologic cycle is of critical importance in the climate system, and one rarely sees a detailed examination of it in climate models. This study indicates that an important and useful component of all future coupled model intercomparison projects should be a summary of the Arctic water budget as in Table 1. The Arctic Ocean is a self-contained subset of the global system where water occurs in all three phases. Modeling the hydrologic cycle in the Arctic region requires modeling the atmospheric precipitation and evaporation, the terrestrial system (river flow and continental ice), sea ice, and the ocean transports of salt, heat, and freshwater. It provides a self-contained system where the model's hydrologic budget can be carefully examined. In parallel with model intercomparisons, the observational network of the Arctic hydrologic cycle should also be improved.

Acknowledgments. Partial support for JRM has been provided under Project #32103 of the New Jersey Agricultural Experiment Station. Additional information about these simulations are available at http://aom.giss.nasa.gov.

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(Received September 22, 1999; revised February 02, 2000; accepted February 23, 2000.)